TOUCH AND TRACE ON THE FREE-FORM SURFACE OF VIRTUAL OBJECT

Yoshitaka ADACHI
RESEARCH & DEVELOPMENT CENTER
SUZUKI MOTOR CORPORATION
2-1 SAKURA-NAMIKI, MIDORI-KU, YOKOHAMA, 226 JAPAN
PHONE +81 45 943 7111 FAX +81 45 943 7100
E-mail adachi@yrd.suzuki.co.jp

ABSTRACT

The Space Perception System with an unique three dimensional(3D) man-computer interface device was built for the experiments. An algorithm using distribution function was utilized to define model shapes in a virtual environment. In this algorithm, the system was able to recognize the interference between the 3D cursor following an operator's hand and virtual objects in real-time. Impedance control of robotics was utilized to calculate a reaction force which was transmitted in real-time from the virtual object to the operator's hand through the 3D man-computer interface device. With the combination of the algorithm using distribution function and Impedance control, the operator could touch and trace on the virtual model which was composed of free-form surfaces in a virtual environment, and could recognize the hardness of it.

1. INTRODUCTION

Virtual reality provides a interface technology which enables us to experience events and acts in a virtual environment just as if we were in the real world. Recently, many virtual reality systems have been developed, and widely used. These systems are very powerful in making the users feel reality in virtual environments. However, there is a slight defect in these systems. These systems provide a good context, yet little or no force feedback. Nowadays, such virtual reality systems can not be said to be enough for all applications.

Over the past few years a considerable number of studies have been made on force feedback. However, surprisingly few studies have so far been made at touch the free-form surface of virtual object. The author's study aims to develop a force feedback technology which is possible to touch and trace on the free-form surface of virtual object. As the sense of touch of human is so delicate that we easily distinguish soft sponge and hard metal, the artificial force feedback should make the operator feel elasticity of the substance.

0-7803-1363-1/93 $3.00

The large problems in force feedback are 1) recognizing the interference between the 3D cursor which is following the operator's hand and virtual objects, 2) calculating the direction of reaction force, 3) calculating the magnitude of reaction force from the virtual object to the 3D cursor, and 4) generating the reaction force to the operator's hand in real-time.

For the problem (1) and (2), an algorithm using distribution function was adopted to define model shapes. For (3), Impedance control of robotics was utilized to calculate the reaction force. For (4), An unique 3D man-computer interface device (SPICE) which had a mechanical structure with actuators to generate the suitable reaction forces was built for experimental use.

2. VIRTUAL MODEL by DISTRIBUTION FUNCTION

In the field of computer graphics (CG), algorithms using density function or distribution function are often utilized to create 3D model shapes. In such algorithms, a model shape is approximated by combined several small balls or ellipsoids, and it is possible to define a complex 3D object with a few amount of data. Consequently, the interference between the 3D cursor and the virtual objects can be verified very fast compared with another algorithms of creating 3D shapes, such as, B-Rpes, CSG, Voxel(Spatial Occupancy Enumeration), Octree, Sweep Representation, etc. Moreover, a surface normal at the point of contact can be confirmed by calculating the distribution function or the density function.

Though many algorithms have been widely published, the algorithm proposed in this paper is so simple and easy to calculate. In this algorithm, a virtual environment is treated as a scalar field, and each point in this field has one potential value which is determined by the distribution function. This algorithm is closely similar to electric potential distribution generated by electric point charges.

First of all, placing one point charge on the origin of the object coordinate system. The distribution function (D) makes a potential distribution in the scalar field. In the system, the following distribution function for a sphere was used.

$$\begin{aligned} D(r) &= W(1-3r^2) && (0 \leqq |r| \leqq 1/3) \\ &= 1.5W(1-r)^2 && (1/3 < |r| \leqq 1) \\ &= 0 && (1 < |r|) \end{aligned} \tag{1}$$

where, r is distance from the point charge, and W is arbitrary value corresponding to electric charge. If one value of the potential (C) is given, the set of solution of following equation will form an equi-potential surface just like a surface of ball.

$$D(r) = C \tag{2}$$

And the set of solution of following equation means the inside of ball.

$$D(r) \geqq C \tag{3}$$

For modeling a complex shape, it is well known that an ellipsoid is suitable for the primitive shape of model. The following scale function expressed in matrix was used to make an ellipsoid.

$$\begin{bmatrix} l \\ m \\ n \end{bmatrix} = \begin{bmatrix} Sx & 0 & 0 \\ 0 & Sy & 0 \\ 0 & 0 & Sz \end{bmatrix} \begin{bmatrix} i \\ j \\ k \end{bmatrix} \tag{4}$$

where u(i,j,k) is the set of solution of distribution function, v(l,m,n) means ellipsoidal shape in the object coordinate system. v(l,m,n) is a mapping onto an ellipsoidal surface from u(i,j,k) on a surface of a ball. Sx, Sy and Sz are scale factors of an ellipsoid.

To distribute the ellipsoid which is defined in the object coordinate system to the basic coordinate system located on a virtual environment, the following movement function expressed in matrix was used.

$$\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} R11 & R12 & R13 & Px \\ R21 & R22 & R23 & Py \\ R31 & R32 & R33 & Pz \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} l \\ m \\ n \\ 1 \end{bmatrix} \tag{5}$$

where, w(x,y,z) means the ellipsoid in the basic coordinate system, Rij are used to rotate a geometry, and Px, Py and Pz are used to translate the origin of the object coordinate system to a point(Px,Py,Pz) specified in the basic coordinate system.

In the case of a complex shape modeling, several ellipsoids are distributed and a composite distribution function (Q) can be defined by the following equation(6).

$$Q(x,y,z) = \sum_i Di(x,y,z) \tag{6}$$

where, Di is the distribution function of each ellipsoid. In the same way, The equi-potential surface formed by ellipsoids is regarded as the surface of virtual object. Fig. 1 shows a simple model made by the algorithm mentioned above.

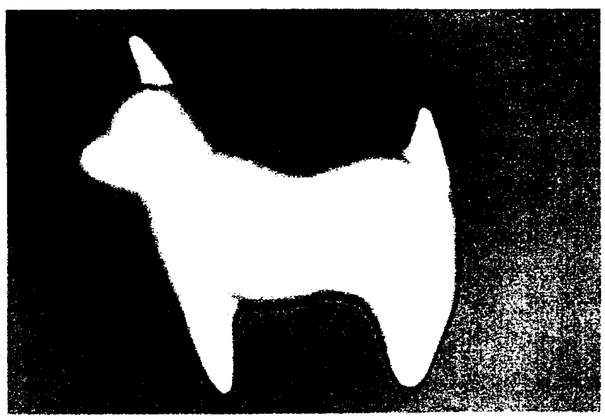

Figure 1 Simple Model by Distribution Function

3. TOUCH on VIRTUAL OBJECT

Control of the 3D cursor presented on a screen by 3D CG is closely similar to the master - slave manipulator technique of robotics. Generally, master-slave control has a slave manipulator which follows to the action of master manipulator. The 3D cursor in a virtual environment is used as the slave manipulator, and controlled by the master.

First of all, the interference between the 3D cursor and virtual objects must be calculated in real-time. In the algorithm mentioned above, the composite distribution functions are calculated on each point, and the surface of virtual object is defined. In the same way, if the potential at the position of 3D cursor is greater than the pre-defined value (C) of equi-potential surface, it is considered that the position is inside of the virtual object. If the potential is smaller than that of the surface, the 3D cursor is outside of the virtual object. Therefore, only the information of the distribution function gives the interference between the 3D cursor and virtual objects.

In our algorithm, calculating time (T) of CPU for confirm the interference between the 3D cursor and a virtual object defined by N ellipsoids can be estimated from the equation(7).

$$T = N \times SQRT + 21 \times N \times MUL + 12 \times N \times ADD \qquad (7)$$

where SQRT,MUL and ADD are operation time of CPU necessary for calculating a square root, a multiplication and an addition respectively. This amount of calculations can be executed in real-time by a micro-processor or a digital signal processor (DSP) needless to use any super-computer.

To generate a suitable reaction force, Impedance control of robotics can be utilized. Fig. 2 shows the concept of the control.

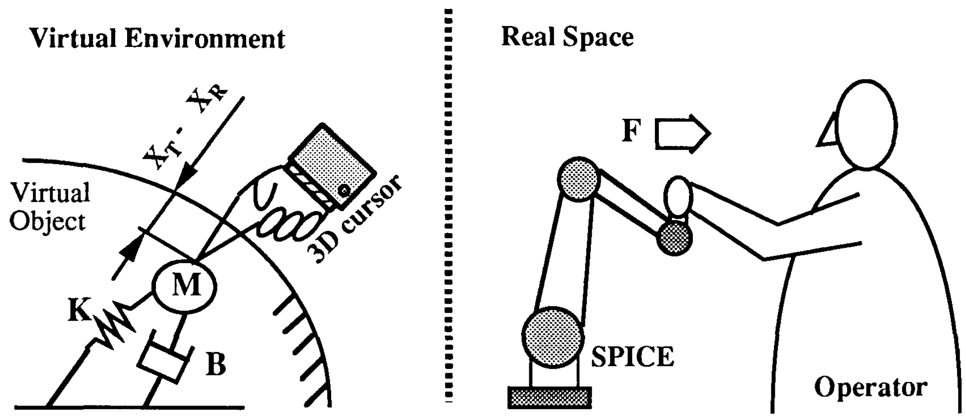

Figure 2 The Concept of Impedance Control

The magnitude of reaction force (F) is expressed by the following equation.

$$F = M\ddot{x}_t + B\dot{x}_t + K(x_t - x_r) \qquad (8)$$

where x_t is the position of 3D cursor, x_r is the position penetrated by 3D cursor on the surface of the virtual object, M,B and K are mechanical impedance parameters of mass, viscosity and stiffness respectively. By changing the parameters, the suitable reaction force just as if we were touching soft sponge or hard iron can be calculated.

Further to get the direction of reaction force, it needs partial differentiation of the distribution function as follows;

$$\mathbf{n} = \left(\frac{\partial Q(x,y,z)}{\partial x}, \frac{\partial Q(x,y,z)}{\partial y}, \frac{\partial Q(x,y,z)}{\partial z} \right) i \qquad (9)$$

where **n** is the normal vector. Then, the torques at each joint of the 3D man-computer interface device (SPICE) can be calculated by the following equation.

$$T = J^T F \tag{10}$$

T is torque and J^T is transposed matrix of Jacobian.

4. EXPERIMENTS

Experiments were performed with the algorithm described above by using the Space Perception System shown in Fig. 3 and Fig.4.

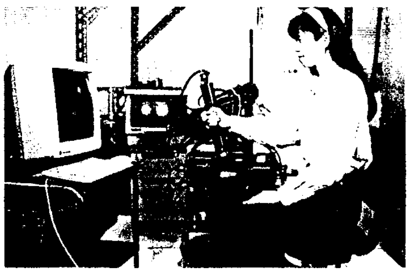

Figure 3 General View of The Space Perception System

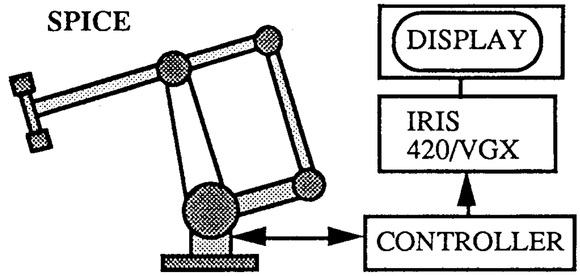

Figure 4 Schematic Structure of The Space Perception System

The system was composed of SPICE, a controller with micro processing units and a display device(IRIS 420/VGX, Silicon Graphics,Inc.). A virtual environment was defined in the controller, and IRIS 420/VGX was used for the virtual environment visualization. Reaction force was generated by SPICE according to the calculations in the controller.

SPICE is shown in Fig. 5 and Fig.6. An articulated structure with six degrees of freedom was employed in SPICE, and each joint was driven by a direct drive (D.D.) motor. The specifications of SPICE are shown in Table 1.

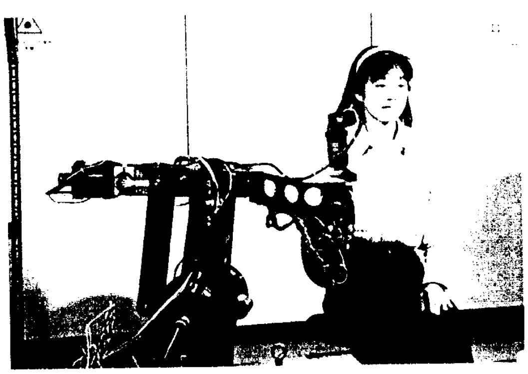

Figure 5 General View of SPICE

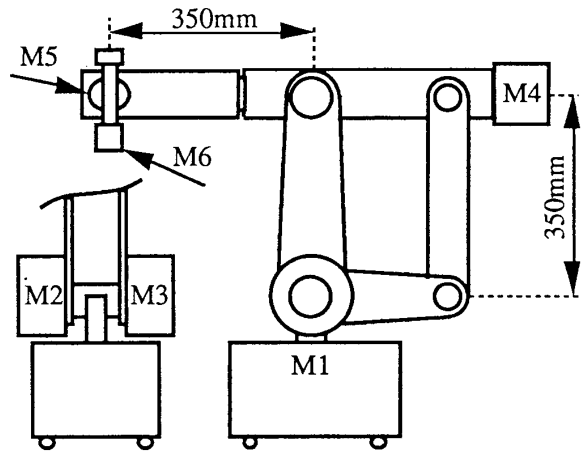

Figure 6 Structure of Mechanism of SPICE

Table 1 Specification of SPICE

Axis	Range [deg.]	Spec. of Max Torque [Nm]	Resolution [pulses/rotation]
1	-70 ~ 70	227.0	324,000
2	-30 ~ 30	189.0	324,000
3	-30 ~ 30	75.8	324,000
4	-90 ~ 90	19.3	10,000
5	-90 ~ 90	3.71	10,000
6	-90 ~ 90	1.66	10,000

An operator seated 100 cm in front of IRIS 420/VGX, and held the grip of SPICE by the right hand. The 3D cursor which appeared on a graphic display followed to the action of operator's hand. The operator could manipulate the grip with a little power and felt a suitable reaction force from the virtual object.

The experiment of tracing tasks were carried out. At first, the operator traced on a surface of virtual peanut-shaped object which had simple distribution functions. The trajectory projected on x-y plane is shown in Fig.7. The cross marks show the movement of 3D cursor at each 60 msec indicate that the operator could trace on the surface of virtual object smoothly.

Then, two objects of different hardness were prepared by Impedance control. The operator traced on the surface of the objects with a constant pressure. The trajectory projected on x-y plane is shown in Fig.8. The cross marks show the position of 3D cursor at each 60 msec. The operator could touch and trace on the surface of the virtual object smoothly feeling the different elasticity and deformation like a rubber ball.

5. CONCLUSIONS

The author has proposed a virtual object modeling algorithm and a reaction force generation method from a viewpoint of force feedback technology. By the algorithm creating the virtual objects, the interference between the 3D cursor and the free-form surfaces of virtual objects is calculated in real-time. Moreover, the direction of reaction force is calculated by the partial differentiation of distribution function, and the magnitude of reaction force is also calculated by Impedance control.

It was revealed by the experiments with SPICE that the operator could easily find the free-form surfaces of virtual objects, and trace them feeling suitable reaction force just as if he were touching real soft sponge or hard metal. The combination of the algorithm using distribution function and Impedance control is suitable to realize the sense of touch by making the reaction force from the virtual object. The experiments indicated that the combination of two methods was very useful and helpful for the force feedback technology of virtual reality.

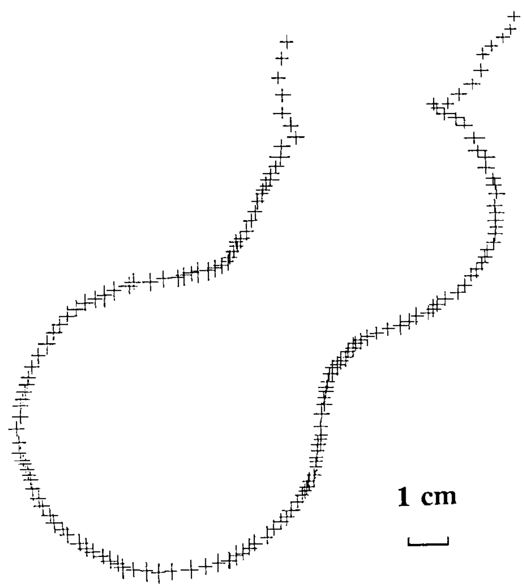

Figure 7 Trace on The Peanut Shape

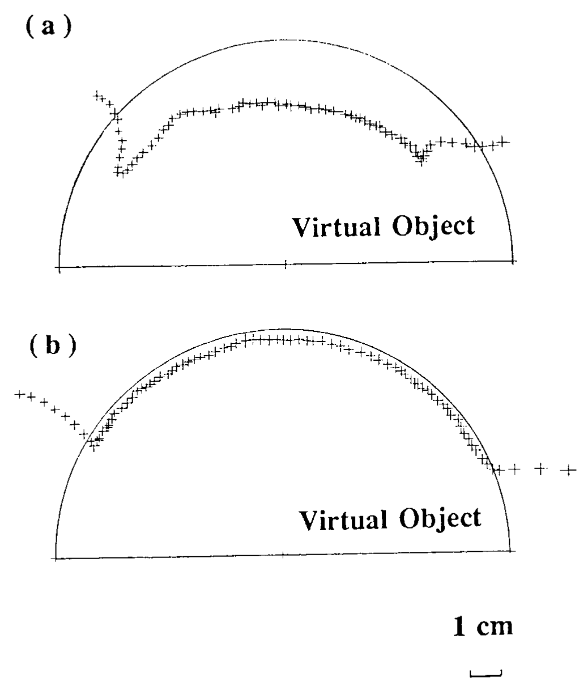

Figure 8 Two Objects of Different Hardness
(a) soft elasticity, (b) hard elasticity

REFERENCES

[1]Y.Adachi, "3D Modeling with Virtual Space", Proc. 1st JAPANESE-FRENCH Congress of MECHATRONICS, Institut des Microtechniques, FRANCE, 1992

[2]H.Nishimura, et al, "Object Modeling by Distribution Function and a Method of Image Generation", Trans. IECE Japan, Part D, Vol. **J68-D**, No. 4, pp. 718-725, 1985

[3]J.F.Blinn, "Generalization of algebraic surface drawing", ACM Trans. Graphics, Vol.**1**, No.3, pp. 235-256, 1982

[4]M.Minsky, et al, "Feeling and Seeing:Issues in Force Display", Computer Graphics, Vol.**24**, No.2, pp. 235-243, 1990

[5]Y.Hirata, M.Sato, "3-Dimensional Interface Device for Virtual Work Space",Proc.The 1992 IEEE/RSJ IROS, Vol.**2**, pp. 889-896, 1992

[6]T.Kotoku, K.Tanie, A.Fujikawa, "Force-Reflecting Bilateral Master-Slave Teleoperation System in Virtual Environment", Proc. i-SAIRAS'90, pp. 295-298